Scientific potential of infrared interferometry from Space

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ABSTRACT

The proposed space interferometry missions of ESA (Darwin) and NASA (Terrestrial Planet Finder or TPF) will be observing in the wavelength region $6 - 20\mu$m. In this wavelength region, the sensitivity of these space observatories will be comparable to NGST, and the angular resolution will be more than an order of magnitude higher. Such a fabulous performance is needed for one of the two main goals of these missions: the detection and characterization of earth-like planets. The second main goal – addressing longstanding and big issues in general astrophysics – will certainly be fully possible with the proposed missions.

In this review we will first briefly discuss the imaging performance of the missions, with an emphasis on the Darwin mission. We will then discuss how these space interferometers will contribute in a very significant way to our understanding of the formation and evolution of planets, stars, galaxies and supermassive black-holes located at the centers of most or possibly even all galaxies.

Keywords: Interferometry from Space, Infrared, Darwin, TPF, Planet formation, Star formation, AGN, Galaxy formation and evolution.

1. INTRODUCTION

The aim of this talk is to discuss the scientific potential of infrared interferometry from space. Given the ambitious programmes that are now being set up both by NASA and ESA to overcome the tremendous technical challenges to operate an interferometer in space, this is certainly an appropriate topic for a presentation at this SPIE conference. From the European side, Darwin, a mission with six telescopes of 1.5 m diameter is under consideration (Fridlund, this conference), while on the USA side the Terrestrial Planet Finder (TPF), a mission with four 3.5 meter telescopes is being studied (Beichman et al 1999). The present projected launch dates for the proposed missions are in 2012. With the tremendous rate that astronomy is progressing in the current "golden age of astronomy", it is a daunting task to layout future observing programmes for these missions. The giant steps forward that astronomy has taken during the last decade have been truly impressive. At the end of the eighties, no significant numbers of galaxies were known with redshifts beyond unity, while now of order a thousand galaxies are known with redshifts in the range $3 < z < 6$ (e.g. Steidel et al. 1999). In those "historic" times of the eighties, only nearby clusters of galaxies were known and it was even suggested that rich clusters only existed in our local universe. At the moment, we know many clusters with redshifts approaching unity. From this we can deduce that the number density of massive clusters at redshifts of order one is even similar to what it is today (Rosati et al. 1998). Also in the area of the formation of stars and planets plenty of break-throughs were reported. Most notable was the detection of a planet-like companion to the solar-type star 51 Peg, providing the first direct evidence for planets around stars other than our sun (Mayor and Queloz 1995). Since this discovery, a number of vigorous searches have been conducted and at the end of last century of order 30 planets have been found (e.g. Vogt et al. 2000). Another highlight was the observations that revealed disks around nearby stars (McCaughrean and O'Dell 1996). These disks are very likely to be the sites where planets originate. A final highlight we would like to mention was the identification of a mysterious gamma-ray burster with a distant galaxy, which showed that at least some of the gamma-ray bursters are of extra-galactic origin (van Paradijs et al. 1997). For all these discoveries the essential tool that drove progress were new instruments capable of sensitive observations in an unexplored region of parameter space. The main reason to firmly believe that the

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rate with which discoveries and breakthroughs will be made will continue for the next 20 years is that in virtually every part of the wavelength region new fascinating instruments will come on line. During this SPIE conference a number of these new observatories will be discussed, including the more than 10 (!) 10-meter class optical telescopes, the successor of HST, NGST (Mather and Stockman, this conference), the (sub) millimetre radio telescope ALMA, and LOFAR, a new radio telescope to be operated from 150 MHz downto the lowest frequencies accessible from the ground (Bregman, Kassim, this conference).

Within this beautiful path for the future of astronomy, the importance of sensitive infrared interferometric observations is immediately apparent. For a number of the most important research areas within present day astronomy, including the formation of stars, planets, massive black-holes and galaxies, crucial information will come from high spatial observations in the thermal infrared. With the planned instruments for ground based interferometry (e.g. the 10 micron instrument MIDI on the VLT interferometer) important steps will be made, but the sensitivity will be limited. The current plan for NGST does include observation up to 30 micron, which is clearly very important. However, with a resolution in this wavelength region of order only a few tenths of an arcsec, NGST will not be able to spatially resolve the essential phenomenon related to the formation of the just mentioned objects.

For this conference, we would first like to discuss some simple but fundamental aspects of (space-based) infrared interferometric imaging. Secondly, we will briefly review the physical processes that emit near-infrared radiation. Finally, we will discuss a number of the most important observational issues that space interferometry will substantially contribute to. These are planet and star formation, active galactic nuclei (AGN) and galaxy formation.

2. IMAGING PERFORMANCE, SOME CONSIDERATIONS

One of the major drivers for the suggested Darwin mission (Fridlund, this conference) is the detection of earth-like planets orbiting nearby stars. In order to be able to do this, the required sensitivity translates to of order a few μJy per hour. We note that the sensitivity of, for example, the VLT interferometer at 10 micron will be more than 3 orders of magnitude less. NGST will have a similar sensitivity, but its spatial resolution will be at least an order of magnitude less. For this talk we will assume that the present Darwin concept with 6 telescopes of 1.5 m passively cooled to 40 K can detect a pointsource of 2.5 μJy at 10 micron in an hour with a signal to noise ratio of 5. The current TPF concept has a sensitivity which is a factor of a few better (one hour of integration for a 5 σ detection at 12 μm of a 0.5 μJy pointsource, Beichman et al 1999). For this presentation we will use the Darwin sensitivities as a guide line. However, virtually all the discussions and conclusions are also applicable to science with TPF, albeit with somewhat shorter integration times. These numbers for the sensitivity should be taken as ball park numbers, and may change in the course of time. However, an earth-like planet in a 1 AU orbit around a solar-type star located at a distance of 10 pc has a flux density of 0.34 μJy (Beichman et al 1999). Given the requirement that such planets should be detectable within integration times of order a few days, these numbers cannot change dramatically.

Since the sensitivities required for the planet finding are so demanding, the mission will be also of great interest for general astrophysical problems. The main astrophysical purpose of Darwin is not to detect point sources – in general NGST will be the preferred machine to do this –, but to image (or at least obtain spatial information on) interesting sources. In the case of interferometric observations of nearby stars the assumption that the stars can be represented by a uniform, or possibly limb-brightened/darkened disks is valid. In general the morphology of the sources to be observe is not known. The morphology can also not be modelled to such an extent that measured visibilities at a few spatial frequencies can reliably be used to adequately constrain these models. Within the radio community, the rule of thumb in such cases is that you can start "imaging" a source, if your total expected flux density within your field of view (FOV) is larger by a factor of order 50 - 100 than the expected off-source RMS noise in your final map. This leads to an "Imaging Requirement" for Darwin, which states that sources should be brighter than $25 - 50\,\mu$Jy to be readily mappable within an hour of integration time.

For a baseline of 100 m the resolution obtained at 10 micron will be 20 mas. Note that this is indeed more than an order of magnitude better than NGST at these wavelengths. For distances up to 200 pc, this gives a resolution of 4 AU, perfect for studying the later stages of the transformation of a dust disk into real planets. In the nearby universe this resolution is ideal for studying the inner part of the accretion disks around active galactic nuclei. For the famous Seyfert galaxy, NGC 1068, which is located at a distance of about 20 Mpc, this resolution corresponds to a few pc, indeed ideally suited to do this. At cosmological distances we know that distant galaxies are small in size, a few kpc (e.g. Giavalisco et al. 1996). At $1 < z < 6$ the physical resolution is of order 0.3 kpc, clearly sufficient to spatially resolve these objects.

Table 1. Important species that can be studies in the mid-infrared

Species	Observables	Physical parameters
Molecules	Rotational and vibrational lines	Temperatures, densities, kinematics, chemistry
Ions	Forbidden fine-structure lines	Temperatures, densities, kinematics, Abundances, excitation mechanisms
Dust	PAH features, continuum shape	Composition, temperature
Late type stars[a]	Continuum	Spatial scales

[a] Note that for high redshift galaxies, the stellar emission shifts towards the mid-infrared.

The point-spread function (PSF) of a 1.5 m telescope observing at 10 micron has a size of 1 arcsec. If only one single PSF from each individual telescope is used in the coherent combination with the other telescopes, the number of independent resolution elements in a map is given by the ratio of the size of the longest baseline over the telescope diameter. This means that in our case maps of maximum of order 75×75 independent resolution elements can be obtained for a set of visibilities with baselines of up to 100 m.

Real astrophysical objects have structures on a vast range of spatial scales, and the issue arises how many UV points are needed to be able to produce an image. A rule of thumb, again stolen from radio astronomy, is that the number of independent UV points needed should be at least larger, but preferably much larger than the number of parameters needed to describe the image. As an example, let us suppose that the central part of 20×20 pixels of the FOV comprises a complex image. To Nyquist sample the UV plane $20^2 \times 2^2/2$ UV point measurements are needed. The reduction with a factor of two comes from the symmetry in the UV-plane due to images only containing non-complex numbers. Note that with the present concept of 6 telescopes, per observation a maximum of 15 independent baselines can be measured. This means that for our 20^2 image of the order of 50 different measurement sets would be needed.

Within the sketched performance, it has been assumed that the array does not need to be phased up using the source that is being observed. With other words, it assumes that the array can integrate on an allegedly empty piece of sky. How to do this in practice is an active area of technical research. At the moment it seems that the best option to phase up the array is to use off-axis bright stars. With an assumed time interval of 10 seconds within which the array is stable, there are sufficient stars that are bright enough so that every object on the sky can be observed (Faucherre, priv. comm.). Alternatively, a system of Kilometric Optical Gyros (KOGs) might be used to monitor the zero optical path difference (OPD) when moving an array that is phased up using a bright star to a faint science target.

A final word on the issue of the size of the field of view. It is clear that from an astronomical view point it is very advantageous to overcome the limitation set by the size of the single PSF of the individual telescopes. Within the present configuration the beam combination is done in the pupil plane, making it non-trivial to enlarge the FOV. Part of the technical research that is being carried out is how to overcome this, without the need for a totally separate beam-combining satellite for the imaging.

3. PHYSICAL PROCESSES AND RADIATION AT SUBMM WAVELENGTH BANDS

The wavelength region from 5 to 20 micron is very rich in diagnostics for a wide range of physical conditions (e.g. van Dishoeck 1999). In table 1, an attempt is made to summarize the radiators, their radiation mechanisms and what physical conditions are being probed by observing in the thermal infrared. Simplifying, gas and dust with temperature in the range of 10 - 10,000 K and relatively high (gas-) densities of $>$ ($>$) 100 cm^{-3} are probed. For high redshift objects, the long wavelength tail of the stellar emission is redshifted into the thermal infrared. We note that one of the important advantages of observing in this wavelength region is that one physical mechanism is not, or hardly operating. This is dust extinction. An object that might be obscured by dust by an amount of 100 mag in the optical will have an extinction close to zero at 10 micron, indeed allowing for an un-obscured view.

4. PLANET AND STAR FORMATION

Based on a wealth of observations a sketch of a scenario how (isolated low-mass) stars form seems to be in place (Shu et al. 1987). The formation of a star commences with the growth of condensations in molecular clouds. When the density of a condensation reaches a critical value, a collapse sets in, on a time scale likely to be governed by the local sound speed. Subsequently a protostar surrounded by an accretion disk forms, both deeply embedded within an envelope of infalling dust and gas. A striking phenomenon during this phase is the occurrence of bipolar outflows. Gradually, the inflowing matter will fall more and more onto the disk rather than the star. Within the final stage, the disk might be fully dispersed by an energetic outflow. Alternatively, the disk material might (partially) coagulate and form one or more planets.

Within the vast range of physical conditions that occur during star formation, the high resolution imaging is particular relevant for spatially resolving core inflow, accretion disks, origin of the jet outflow and planet formation. Establishing the density, temperature and dynamical structure of the core inflow and accretion disks would be an essential constraint on the proposed models of the physics of these structures. Furthermore, it is not well understood how the jet outflow originates from the accretion disk. How does this start? What keeps the jet stable? High resolution imaging of the jet-formation region would yield valuable insights. For the planet formation there is a list of outstanding questions that space interferometry can address, including, what fraction of the disks are forming planets, at what stage in the accretion process are planets formed, what density, temperature and kinematic structure do the disks from which these planets are forming have?

5. ACTIVE GALACTIC NUCLEI

Active galaxies have compact nuclei that can be so luminous that they can outshine a whole galaxy. These cosmological beacons are so bright that they can be seen out to the earliest 5 % of the age of the Universe. At early times ($1 < z \lesssim 5$) these active objects are a factor $100 - 1000$ more common than in our local universe. There is much evidence that they contain massive black–holes, the central engine of the physical processes that give rise to a large number of energetic phenomena. The most important questions in this area undoubtedly include the relation of the AGN phenomenon to galaxy formation, and the physics of the formation and evolution of the massive black-holes. A recent clue to answering these questions is the strong indication that a large fraction of local galaxies contain massive black-holes, and that the mass of the black-hole directly scales with the mass of the spheroidal component of the hosting galaxies (e.g. Kormendy and Richstone 1995).

The now canonical view of AGN is that they are powered by the exchange of gravitational energy for thermal energy in a compact accretion disk surrounding a massive black-hole (e.g Rees 1984; Gallimore 1997). In the currently popular and attractive "unified" model of active galactic nuclei, all AGN host an optically thick obscuring torus; its orientation with respect to our line of sight determines whether we see the object as a Type I (Seyfert 1 or quasar) or Type II (Seyfert 2 or radio galaxy – for reviews see Antonucci 1993 and Urry and Padovani 1995). A cartoon of the unified model for the heart of the AGN is presented in Figure 1. The inner accretion disk which feeds the massive black-hole directly is surrounded by the "broad-line region". In this region dense compact clouds move at a high speed through a more tenuous medium giving rise to broad optical emission lines. The broad-line region is surrounded by an optically thick torus composed of dust and molecular and neutral gas. If the torus hides the central region from our view, the direct high energy phenomenon associated with the very central part of the region is more difficult to observe. The object does not show broad lines and is classified as a Type II object. If the object is observed sufficiently close to its polar axis, a very bright nucleus is observed and the optical spectrum will exhibit broad lines. It will be classified as a Type I.

Although this picture is capable of explaining a large number of the differences between the various classes of AGN (e.g. Antonucci 1993), there is still a vigorous debate as to whether other mechanisms contribute to, or even dominate over, the scenario in which orientation and a putative torus play such a major role. It has even been argued that in a subset of AGNs, the main power-source is not a black-hole, but supernovae explosions produced within a central starburst region. Another interesting suggestion is that time variability plays an important role in understanding differences between AGN. In the sources that show a bright nucleus the AGN is being actively fed, whereas in the sources that do not show such a bright nucleus, the feeding has been (temporarily) stopped.

A number of models for obscuring tori have been proposed (e.g. Pier and Krolik 1992; Efstathiou and Rowin-Robinson 1994; Krolik and Begelman 1988; Granato et al. 1997). The models range from extended 100 pc-scale tori having a moderate optical depth to much more compact tori with very high optical depth. Also several geometries have been investigated, including structures with a warped disk (Sanders et al. 1989). It must be stressed however, that there are a number of serious difficulties with these models. For example, it is generally assumed that the

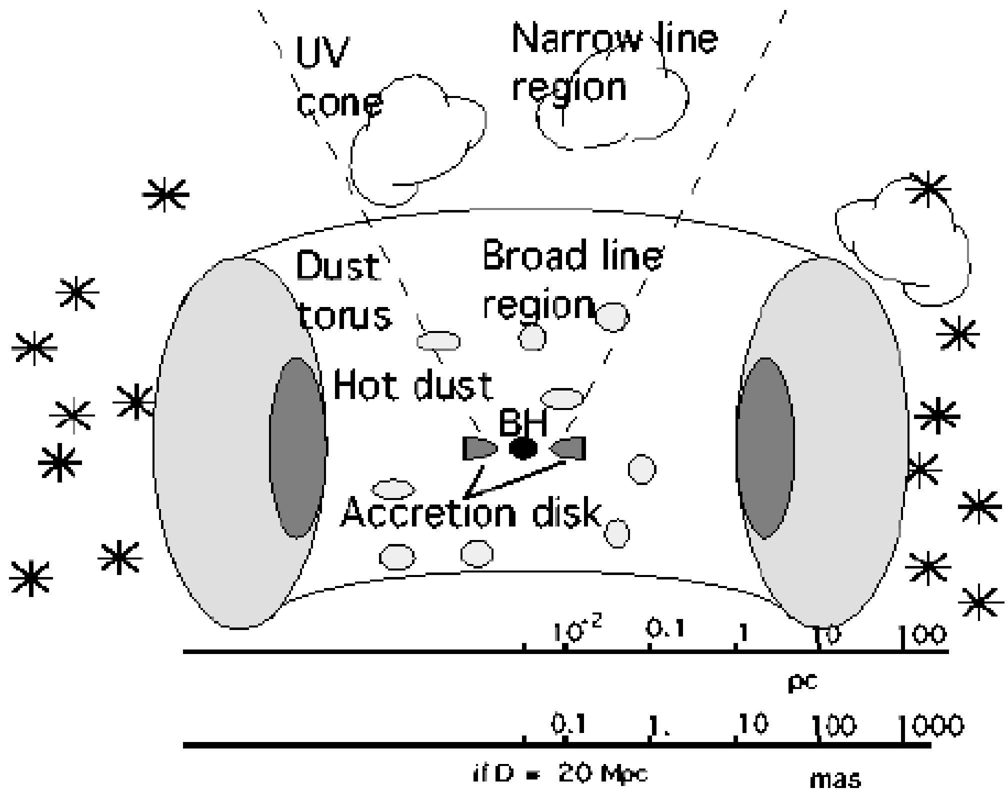

Figure 1. A cartoon of the heart of the AGN, indicating several of the components.

tori are composed of dusty molecular clouds with a large cloud velocity dispersion. How such an assembly can be maintained is an unsolved theoretical problem (e.g. Maloney 1998).

High resolution imaging at 10 micron of nearby active galaxies has a crucial role to play. At 10 microns the view towards the heart of the galaxy is not hampered by extinction due to dust in the galaxy and is not confused by stellar emission. This should therefore allow the unambiguous detection of dust tori. It will further constrain a number of important physical parameters of the torus, including the inner and outer radius, its density, temperature and kinematical structure.

For a first indication of what structures can be expected to be observed, we use the models of Granato et al. (1997). In these models the radiative transfer through the dust is calculated for axially symmetric tori. Important input parameters are the line of sight optical depth and the orientation. The resulting IR spectral energy distribution can then be compared with what is observed. Furthermore, the morphology of the torus as a function of wavelength is predicted. As a test case we use the canonical Seyfert 2 galaxy NGC1068 for which several recent observations suggest the presence of a molecular/dusty torus with a temperature of 1500 K near the core and 600 K at 15 pc (Gallimore et al 1997, Rouan et al 1998, Marco and Alloin 2000, Tacconi et al 1997). The fit to the nuclear spectrum of NGC 1068 is obtained with a visual extinction of $A_V \sim 72$ mag along the line of sight, and an orientation of 65° (Granato et al 1997). In Figure 2, we show the resulting morphology for this particular model, but with line of sight optical depths of $A_V = 30$ and 150 and orientations of 60° and 90°.

It is very clear that Darwin will be able to very nicely map nearby tori. An interesting question is to what distance tori of AGN can be mapped. To investigate this, we again will use the models of tori of AGN of Granato et al. 1997. A first thing to note is that the inner radius of these tori, $r_{\rm in}$, is set by the distance from the central source at which the dust grains sublimate due to the strong nuclear radiation. This radius is larger for more luminous AGN. For the

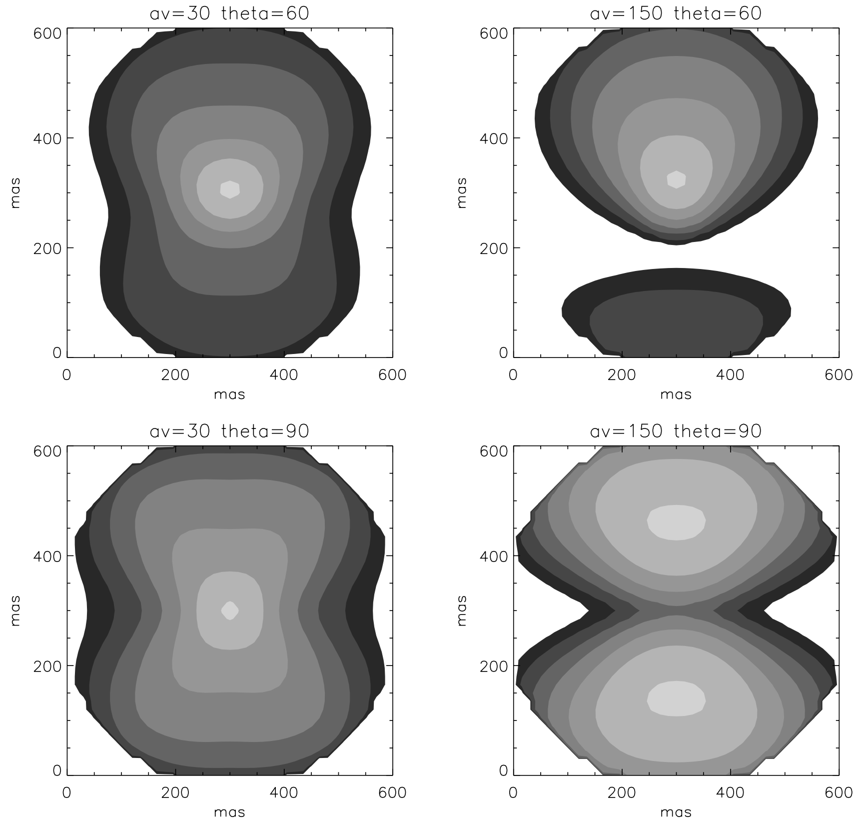

Figure 2. Greyscale presentations of the morphologies at 10 micron according to the model for NGC 1068 of Granato et al. (1997). The optical depths vary with visual extinction $A_V = 30$ and 150 mag and the orientations vary with theta = 60° and 90°.

models of Granato et al, $r_{\rm in} \sim 0.5 L_{46}^{1/2}$ pc, where L_{46} is the luminosity of the central optical UV emitter in units of 10^{46} ergs s^{-1}. As a scale size of the torus D we will use 300 $r_{\rm in}$. In Figure 3, the diameter D and the 10 micron luminosity (which are directly coupled) are given as a function of z for angular scales of 1, 0.1 and 0.01 arcsec. The dotted lines correspond to the 10 micron luminosities as a function of z for 10 micron flux densities of 5 and 50 μJy.

A relatively weak AGN such as NGC 1068 has a 10 micron luminosity of the order of 1.7×10^{31} erg s^{-1} Hz^{-1} and its modelled torus size is 60 pc. Up to redshifts of $z = 1-2$ such weak AGN are brighter than the nominal sensitivity for a one hour imaging observation (see Section 2) of $25 - 50 \mu$Jy. Also the nominal resolution at 10 micron of 20 mas is very adequate for imaging the tori at these redshifts. Brighter AGN can basically be mapped up to redshift of $z = 10 - 20$ (if they exist).

This shows that Darwin can not only study the physics of dusty tori in our local universe, but also at large redshifts. This will give the unique opportunity to investigate how the properties of tori change with redshift and when and how these tori and their associated massive black-holes are build up at an epoch when galaxies are forming.

6. GALAXY FORMATION

With the advent of 10-m telescopes, it is now possible to define large samples of very distant galaxies. This work has been pioneered by Steidel and coworkers. Using the "Lyman break technique", they have defined a sample containing of order a 1000 galaxies between $2.5 < z < 5$ (e.g. Steidel et al. 1999). No systematically defined samples of galaxies exist with redshifts over 5 and up to now, only a handful of galaxies with $5 < z < 6$ has been reported (Stern et al. 1999). At this SPIE conference Renzini made the prediction that the number of spectroscopically confirmed > 5 galaxies will approach a thousand within the next decade. For the large existing sample of Lyman break galaxies, the measured colours and structural parameters allow for extensive studies of the general galaxy population at high

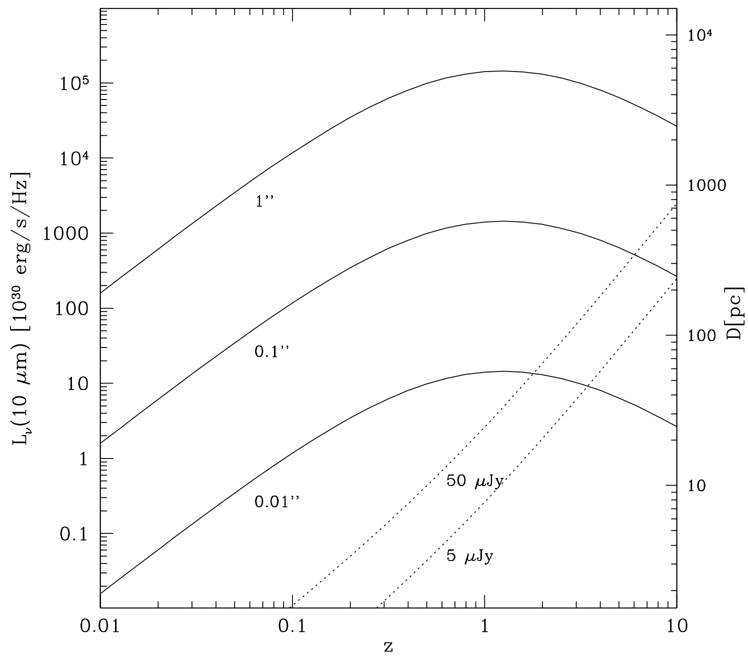

Figure 3. The 10 micron luminosity and physical scale D of dusty tori as a function of redshift. The solid lines are for observed angular scales of 1, 0.1 and 0.01 arcsec. The dotted lines are for an observed 10 micron flux density of 5 and 50 μJy. The computations have been done for $H_0 = 75$ km s^{-1} Mpc^{-1} and $\Omega = 1$.

redshifts. Issues that are being studied include the importance of dust, average star formation density, and the clustering properties of the distant galaxies.

This amazing observational progress of the last 10 years has been accompanied by a large body of work to build reliable and robust models of galaxy formation. The goal is to model the evolution of galaxies with, as the main input, the physical conditions as they existed in the very early universe. For a thorough account I refer to a few of the excellent articles and reviews that have been written (see for example: Rees and Ostriker 1997; White and Rees 1978; Baron and White 1987; White and Frenk 1991; Cole 1991; Lacey and Silk 1991; Kauffmann et al. 1993; Lacey et al. 1993; Cole et al. 1994; Kauffman et al. 1994; Baugh et al. 1996; Baugh et al. 1997).

Virtually all of the current models assume that the dynamics of the large scale mass distribution in the early universe is driven by the gravity exerted by some form of dark matter. At early times the density fluctuations within this medium are modelled by a described distribution whose functional form depends on the physics in the early universe, the nature of the dark matter and the suitable choice of cosmological parameters. The evolution of the dark matter distribution can be studied analytically or with the help of N-body simulations. A second step is to include the baryonic gas and to follow its hydrodynamic evolution. Gas dynamics, shocks and radiative heating and cooling all need to be part of the simulation to obtain a realistic multi-phase medium. The outcome of this kind of simulation is that a significant fraction of the gas cools and settles at the centres of dark matter halos. It is from that gas that the stars that will make up future galaxies will form. Often it is then simply assumed that the rate at which the gas at the center of these halos forms stars is proportional to the total amount of gas present and inversely proportional to the dynamical timescale within the dark matter halo. The rate with which these proto-galaxies form stars is limited due to both supernovae and stellar winds which blow gas out of the centers of these halos. The merging of galaxies greatly enhances the combined star formation rate of both galaxies, possibly to a rate whereby a very large fraction of the gas is transformed into stars within a few dynamical timescales. Finally, the combination of the inferred star formation rate, an assumed initial mass function and the spectral evolution of individual stars will then give the evolution of the integrated spectra of an individual galaxy. With this kind of modelling gross

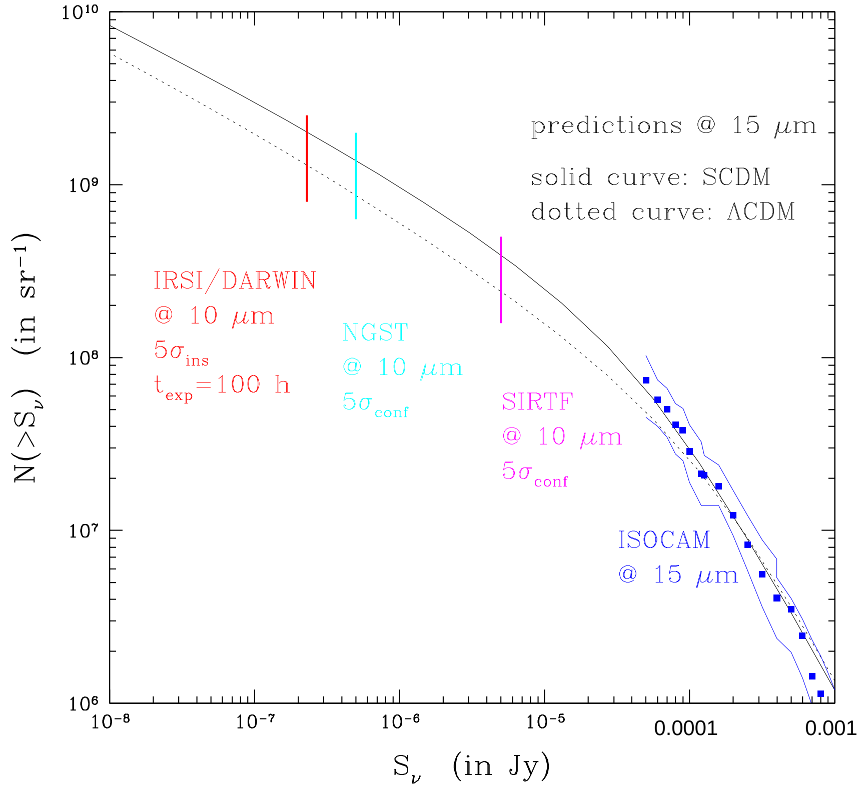

Figure 4. The predicted source counts at 15 micron from the semi-analytic models for galaxy formation of Guiderdoni and coworkers. The solid curve is for a standard CDM and the dotted curve for Lambda CDM. Overlaid are the ISOCAM souce counts at 15 micron. Further is indicated the ultimate limits for SIRTF, NGST and Darwin.

properties of the general galaxy population can be calculated. These properties include the luminosity function of galaxies, the redshift distribution, the relative numbers of ellipticals and spirals, faint galaxy counts, the history of star formation etc.

What role will Darwin have to play in this area? Maybe it is important to realise that even 10 years from now the issue of how galaxies form will still be one of the most important topics within the field of astronomy. Or to quote Rees (1998) from an address about NGST, who states that in 10 years from now, "we will probably still be unable to compute crucial things like the star formation efficiency, feedback from supernovae. etc – processes that current models for galactic evolution are forced to parametrise in a rather ad hoc way".

An essential constraint on these galaxy formation models will be to probe the spatial structure of very distant galaxies at $1-2$ micron restframe, the location of the peak of the spectral energy distribution of nearby galaxies. For $z \sim 5$ galaxies, this region is redshifted into the spectral window within which Darwin will be observing. From HST imaging we know that the $z \sim 3$ galaxies are only a few tenth of an arcsec in size (Giavalisco et al. 1996) and there are good reasons to believe that more distant galaxies will be even smaller. NGST at 10 micron will not have the resolution to spatially resolve these distant objects, but the proposed interferometer missions will.

The crucial question is whether there are sufficient number of distant galaxies on the sky that can be usefully observed. The answer is yes, and on this we will elaborate in two ways. First, we will use the models of galaxy formation of Guiderdoni and coworkers (Guiderdoni et al. 1998, Devriendt et al. 1999, Devriendt & Guiderdoni 2000) to make a prediction of the number of observable galaxies. Second, we will present some very nice VLT imaging in the near infrared from the VLT FIRES survey (Franx et al. 2000) that indicates that there are plenty of distant

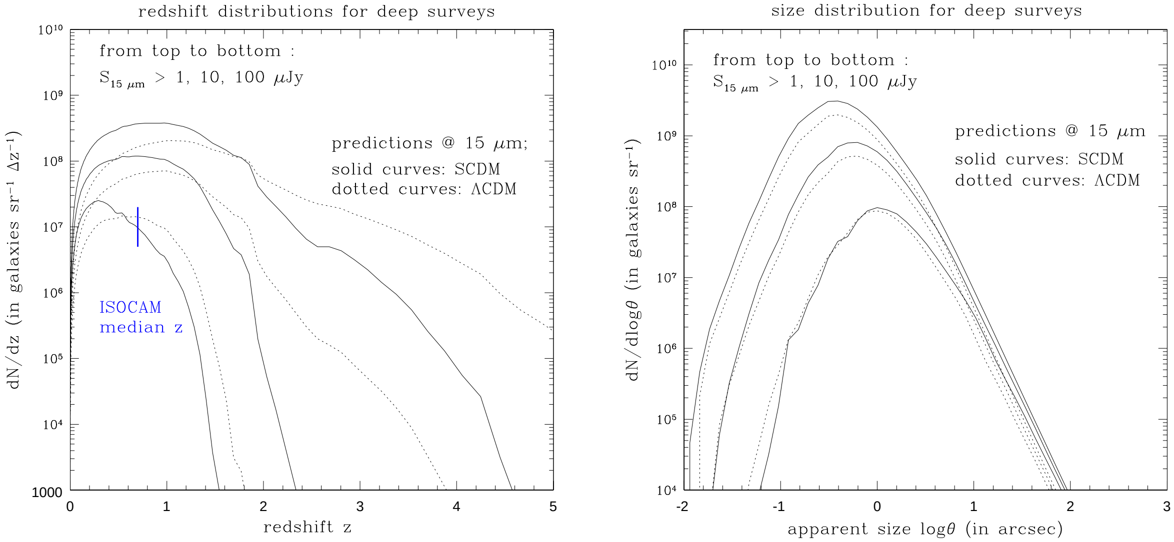

Figure 5. The redshift and angular size distributions for surveys at 15 micron to a limiting depth of 1, 10, 100 μJy. as predicted from the semi-analytic models for galaxy formation of Guiderdoni and coworkers. The solid curves are for a standard CDM and the dotted curves for Lambda CDM.

targets for Darwin.

Recently there have been a number of attempts to capture the general scenario for galaxy formation as we have described at the beginning of this section in the form of a number of simple prescriptions. The power of these "semi-analytic models" is that they can make testable predictions of the global properties of the galaxy population and its evolution. Recently, a number of groups have attempted to include the role of dust in these models. This is clearly important since dust can affect the observed characteristics of (distant) galaxies in a number of major ways. For example, through dust extinction, galaxies with high star formation rates might be totally hidden from our view in the optical part of the spectrum, whereas they can be very bright in the infrared.

To illustrate the power of Darwin's ability to detect and study distant galaxies we have used the models of Guiderdoni et al. It is very appropriate to use these models since they include the extinction and emission of dust and as such the models correctly fit the ISO 15 μm source counts. In Figure 4, we show these ISOCAM source counts plus their fit from two models (Standard CDM and Lambda CDM). From this plot there are a number of noteworthy points. According to these models, at 10 micron, deep NGST imaging will be limited by confusion and in theory Darwin could go deeper. Whether or not it would make sense to aim for "a Darwin deep field" will depend on the FOV of the final design. A deep survey at $10-15$ μm with an exposure time of 100 hours, would contain about $100-200$ objects per arcmin^2. This shows how important it would be to investigate possibilities of enlarging the field of view over one single PSF of 1 arcsec. The models indicate that for such a deep survey the redshift distribution would have a median of $z \sim 1.5$ and long tail towards high redshifts; the median size of the galaxies would be about 0.3 arcsec. Finally, from Figure 4 it is clear that known ISOCAM or future SIRTF sources should all be observable with Darwin.

To further investigate what kind of sources are observable with Darwin, we show the predicted redshift and angular size distributions for surveys of various depths (see Figure 5). From these models it is clear that bright ($> 100\mu$Jy) 15 micron sources have a median redshift close to unity and that there are virtually no sources with a redshift $z > 2$. For the fainter surveys, the predicted range in redshifts is a factor of 2 more. Note, that the high redshift tail of the distribution is still rather uncertain. However, we can be sure that this will be constrained to a large extent before Darwin flies. From the angular size distribution (Figure 5) it is apparent that a large fraction of the fainter sources – and these will be preferentially the higher redshift sources – have angular sizes for which Darwin can make nice maps.

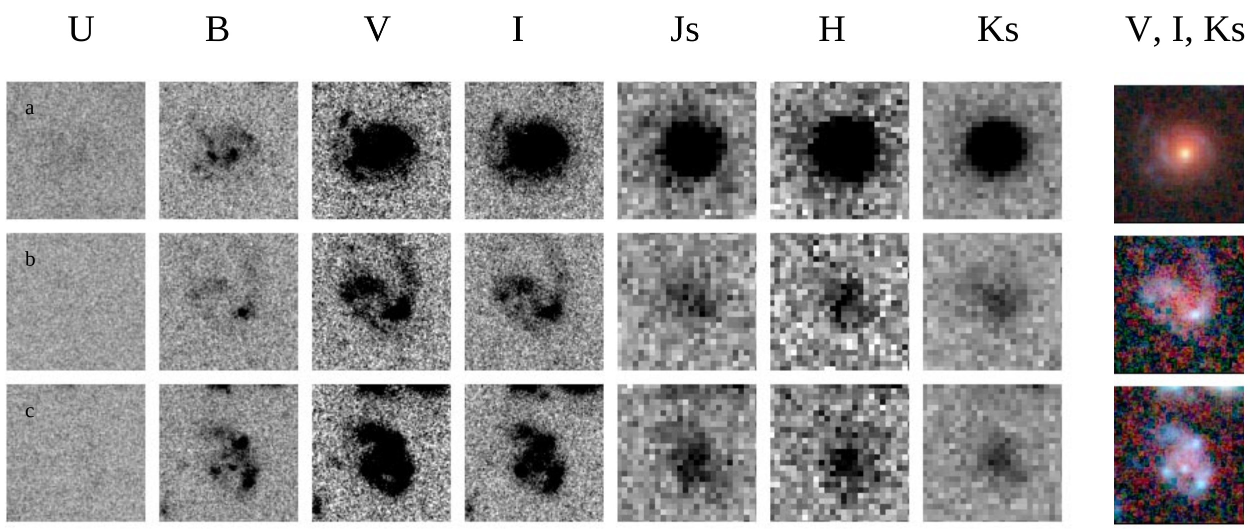

Figure 6. A closeup of several high redshift galaxies in the Hubble Deep Field South (from Franx et al. 2000). The individual panels show the images of the galaxies in the optical from HST (U, B, V, I), and in the infrared from the VLT (J_s, H, K_s). The differences in morphologies from band to band and from galaxy to galaxy are quite striking.

The main observational constraints relevant for observing distant galaxies with Darwin are the 15μm ISO source counts. Using the models of Guiderdoni et al., these have been extrapolated to fainter flux densities and somewhat shorter wavelengths. Since very sensitive observations at K-band (2.2μm) can now be carried out with the presently available 10-m class telescopes, an alternative route is to use these observations and meaningfully extrapolate them towards the longer wavelength at which Darwin is operating.

For this purpose we will use the first preliminary results from a new survey using the VLT, the Faint InfraRed Extragalactic Survey (FIRES, Franx et al. 2000). The main aim is to study the distant galaxy population, albeit that many other applications of this survey can be foreseen. This survey has been carried out using ISAAC, the new infrared instrument on the VLT and will consist of very deep images in the J_s, H, and K_s bands, each 2.5×2.5 arcmin^2 in angular size. One of the fields of the survey is the Hubble Deep Field South for which deep HST imaging data in 4 optical bands exists. In this area, each of the three bands will be observed for 24 hours, yielding an expected depth in K_s of 24.4 mag (3σ). The first part of the data has been taken at the end of 1999 and consists of 4, 4 and 8 hours in the J_s, H, and K_s bands respectively. In Figure 6 we give a montage from Franx et al. (2000) of three of the galaxies in the field. Each of them has a likely redshift well over 2.

At the moment a programme is being carried out to fit a range of template spectra to the broadband HST and ISAAC flux densities, so that for each galaxy a photometric redshift can be obtained. The first preliminary results indicate that at least a handful of $z > 2$ galaxies within this survey should be observable with Darwin with an integration time of a few hours. We note that the robustness of this conclusion and a 10 μm luminosity function for various redshift ranges need further investigation. We further note that the template spectra do not contain a contribution of dust emission longword of a few microns. In this respect, the number of observable galaxies is likely to be more than indicated from the present analysis. Concluding, from the ISO counts and the FIRES field it is clear that Darwin will be able to do very important work in imaging very distant galaxies.

7. CONCLUSION

The scientific potential of the two proposed space interferometric missions, Darwin and TPF is tremendous. With the present performance of μJy sensitivity and tens of mas angular resolution, they will allow for detailed studies of a number of crucial questions related to the formation and evolution of planets, stars, AGN and galaxies.

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